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SENSOR REQUIREMENTS FOR ACTIVE GAS TURBINE ENGINE CONTROL

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1. ABSTRACT

This paper considers the potential benefits of active gas turbine engine control and briefly reviews a selection of the published material in the fields of detection and control of stall in axial flow turbomachines from the perspective of an instrumentation engineer. The use of a variety of sensors and mechanical installations is discussed and a specification for a pressure sensor which can be used to detect gas path instabilities in axial flow compressors is developed.
Recent developments of Silicon-On-Insulator (SOI) piezoresistive pressure sensors for gas turbine research and development and basic aerodynamic research are described in this paper. Problems which can arise from use of these sensors in ultra harsh environments are discussed. The design of a new miniature dynamic pressure transducer capable of operating reliably under extreme environmental conditions - temperatures in excess of 480°C (900°F) and accelerations greater than 200g - is described in detail. The performance of such "leadless" pressure transducers is presented and indicates that ruggedised, high frequency, piezoresistive transducers are now feasible for use in the dynamic control of turbomachines.

2. INTRODUCTION

The modern aero gas turbine engine is generally considered to be a relatively mature device, having been the subject of intense development throughout the world for over half a century for both military and civil applications. Consequently the cost and difficulty of achieving further improvements to the gas turbine in terms of specific fuel consumption, weight and price have risen steeply. However the explosive growth in computing and microelectronics gives rise to optimism in achieving dramatic improvements in the performance of gas turbines in the future when this technology is applied to engine control systems. Significant improvements have already been made in the performance, economy and handling of modern gas turbine engines by the use of Full Authority Digital Engine Control systems (FADEC). Many modern turbomachines, in particular multistage axial flow compressors, now rely on complex scheduling of stator vanes and bleed valves and monitoring of pressures, temperatures and flows to achieve stable operation. The ability of a FADEC to process the many sensor inputs from an engine, to apply sophisticated control laws and control a range of actuators simultaneously, enables many modern gas turbines to function economically and reliably. A return to the previously used hydro-mechanical control systems would, in many cases, be impossible without significant mechanical and aerodynamic redesign of the turbomachine.
The modern FADEC controls the starting, steady operation and transient conditions of a gas turbine and incorporates fault tolerant designs appropriate to a flight critical system. The next step which is predicted will generate a significant improvement in efficiency of operation of a gas turbine has been identified as the improvement in stability of compressors through the anticipation and suppression of surge and rotating stall. The natural aerodynamic instabilities of turbomachines often limit their performance, but increased stability potentially leads to lighter more efficient compressors with fewer stages and shorter airfoil chords, reduced fan noise from lower tip speeds, faster engine acceleration as the surge constraints have been removed and greater operating flexibility.
The subject of the control of stall and surge in turbomachines has been investigated widely with Ludwig's work in 1980 being the earliest identified reference [1]. However the phenomenon of stall and surge in the compression systems of gas turbine engines has been the subject of investigation since the 1950s. Twelve teams have been identified through a non rigorous review of the published technical data in this field [2] and in addition, there

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are other currently active teams who eschew publicity.

3. SENSOR SELECTION

The selection of the sensor type and location(s) are critical factors in determining the effectiveness and practicality of an engine surge and stall control system, as is the selection of the actuator type and the algorithms used to process the data from the sensors. This paper will confine itself to the issues relating to the choice and design of the sensors, although similar importance needs to be attached to the selection of the actuators and signal processing software and hardware in order to create an engine control system which is both effective and safe.

A review of the most recently published material in the field of active control of surge and stall in axial flow compressors concludes that the most widely used physical parameter to monitor the stability of a compressor is pressure, although the measurement of gas flow using hot wire anemometers and the measurement of gas temperature using high response thermocouple probes have been used successfully.

The paper by Day, Breuer, Escuret, Cherrett and Wilson [3] assessed the generic features of stall inception using four high speed compressors. In the experiments on all four compressors, large numbers of miniature Kulite pressure transducers were used (MTU – 24, DRA – 24, SNECMA – 40, Rolls-Royce – 27). Similarly in the reported work by Freeman, Wilson, Day and Swinbanks [4] on the applied stall control of a Rolls-Royce Viper engine, 30 miniature Kulites were employed. In addition, the work by Eveker, Nett and Sharma on the demonstration of a non-linear control strategy on a high speed 3 stage axial flow compressor used 15 miniature Kulites. The paper by van Schalkwyk, Paduano, Greizer and Epstein [5] describes the first experimental validation of transfer function modelling and active stabilisation on a 3 stage low speed axial flow compressor and is the exception in the use of 8 hot-wire anemometers, which measured the gas flow, as the sensors for the control system.

DiPietro and O'Brien [6]and [7] report on the effects of transient inlet temperature fluctuations on the stability of a 2 stage subsonic axial flow compressor using medium response thermocouples and static and pressure tappings connected to Datametrics and Omega pressure transducers.

4. SENSOR INSTALLATIONS

In the experimental work referred to in the previous section, the pressure transducers have been physically installed in a compressor in two configurations to sense the stability of operation of the machine by the measurement of high response pressure fluctuations. First the transducer can be attached to a total pressure pitot probe and can be either embedded within the probe or mounted remotely using a non-resonant pipe system, or semi-infinite line, as shown in Figure 1.

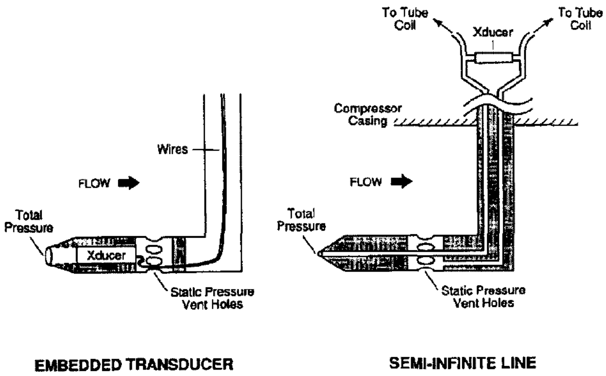

Figure 1

The second configuration is referred to as a wall static installation with the pressure transducer either directly mounted in the wall of the compressor casing with a flush sensing diaphragm or remote from the static tappings using a non-resonant pipe system similar to that referred to in the pitot probe configuration and is shown in Figure 2.

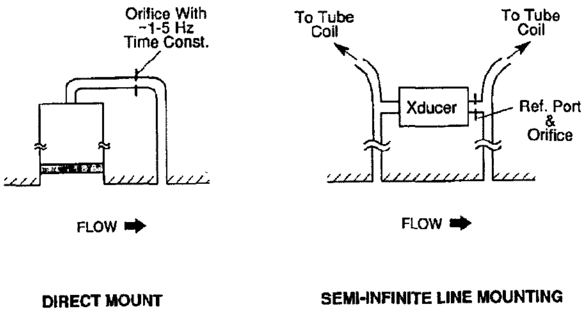

Figure 2

Both configurations have strengths and limitations; the measurement of dynamic total pressures using the pitot probe potentially generates the largest unsteady pressure signals under stall and surge conditions but is intrusive which may affect compressor efficiency and weight, especially if multiple probes are required. Additionally, a long experience of working closely with compressor designers suggests that they are likely to be unhappy with a significant increase in the quantity of intrusive gas path instrumentation from the perspectives of reliability and efficiency.

The wall static installation typically generates dynamic pressures which are approximately half the amplitude of the signals produced from a total pressure pitot installation under similar conditions. However the wall static installation is mechanically superior in that it is non-intrusive and hence is unlikely to affect aerodynamic efficiency or weight and will be more reliable.

On the basis of the above considerations, the authors are of the opinion that the wall static configuration is the one which is most likely to be selected for application to production gas turbine engines. A flush diaphragm arrangement is also likely to be more acceptable thus avoiding the additional cost, weight and complexity of semi-infinite line systems.

5. PRESSURE SENSOR SPECIFICATION

The high response pressure data which is generated by the dynamic pressure transducers is processed using one of many proprietary algorithms in order to predict or detect the onset of stall and surge. Although the operation and logic of the algorithms described in the technical publications vary considerably, the data requirements from the pressure sensors appear to be remarkably similar. The required characteristics for a stall and surge pressure sensor have been derived from both published technical papers and informal discussions with leading researchers in the field.

The pertinent characteristics which are required of a compressor mounted stall and surge pressure sensor are high sensitivity (ability to detect 70Pa (0.01psi) peak to peak fluctuations), stability of sensitivity with temperature and time (±5% to 10% FS) and the ability to survive in an extremely hostile environment (operating ambient temperatures and transients between -54°C and 400°C (-65°F and 750°F) and acceleration levels of up to 200g peak between 1kHz and 18kHz). The pressure transducer installation should also have sufficient bandwidth to measure frequencies between 100Hz and 1kHz for large gas turbines and between 500Hz and 8kHz for small gas turbines with negligible phase shift. During surge conditions, the pressure transducer must survive gas path pressure and temperature transients of up to 3.4MPa (500psi) and 1000°C (1830°F) for several seconds. Finally, if active surge and stall control systems are to be applied to production civil and military gas turbine engines in the future, the reliability and cost of the dynamic pressure transducers must be competitive with the pressure transducers currently used to measure oil, fuel, air and hydraulic pressures on airframes and engines.

6. THE SILICON-ON-INSULATOR (SOI) SENSOR

For the last 40 years, Kulite has supplied high performance pressure transducers to the aerospace industries for both research and development and for production applications. These transducers are based upon the piezoresistive silicon technology which Kulite pioneered and developed to its current high levels of performance and reliability. In order to describe the research and development which has led to the creation of the leadless pressure transducer, it is relevant to consider the original silicon-on-insulator pressure capsule design.

The heart of the piezoresistive SOI pressure sensor is a silicon diaphragm which is supported upon a Pyrex glass pedestal in such a manner as to enable a pressure differential to be applied across the diaphragm without introducing a mounting strain in the diaphragm. An "anodic" molecular bond is used to attach the silicon diaphragm to the glass pedestal which ensures a very stable, permanent assembly without the use of glues or adhesives. Piezoresistive silicon strain gauges are integrated within the silicon diaphragm structure but are electrically isolated from the silicon diaphragm as shown schematically in Figure 3. The piezoresistors measure the stress in the silicon diaphragm which is a direct function of the pressure of the media.

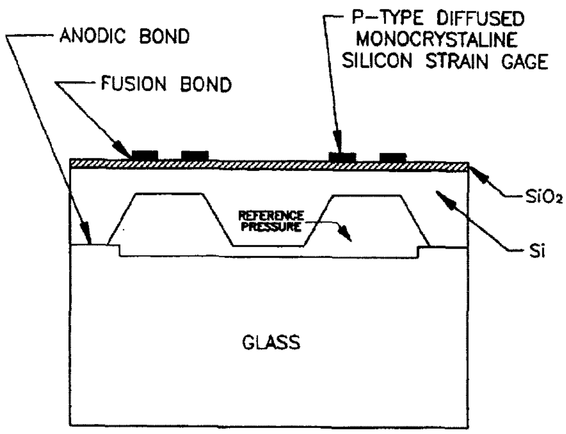

Figure 3.

The silicon diaphragm is usually thinned in selected areas underneath the piezoresistors by anisotropic chemical etching in order to increase the pressure sensitivity of the diaphragm. A photograph of the top of a silicon diaphragm is shown in Figure 4.

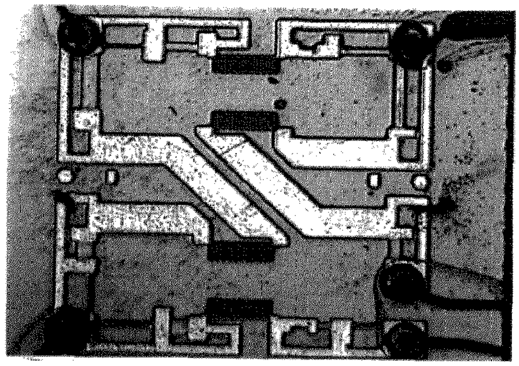

Figure 4.

The photograph clearly shows the four darker piezoresistors which are connected electrically via the lighter coloured metallic interconnections to form a fully active Wheatstone bridge. Also clearly

visible at the corners of the diaphragm are five 0.024mm (0.001 inch) diameter gold bond wires which are ultrasonically ball bonded to the diaphragm metallisation and are used to connect electrically to the bridge.
Under extreme conditions of temperature and vibration, the ultrasonic agitation used to form the ball bonds causes abrasion to take place during the welding process and allows microscopic holes to develop in the platinum metallisation through which, at high temperatures, the gold can migrate and form a gold-silicon eutectic which causes the leads to fail. In addition, the pressure media is in direct contact with the stress-sensing network, leadouts and interconnects which at high temperatures and in the presence of aggressive chemical can fail. The key elements in the design of a ruggedised pressure sensor is the elimination of the gold bond wires and the protection of the sensing elements from corrosive environments at high temperatures, hence the reference to the new sensor capsule as the "leadless" design.

7. LEADLESS SENSOR DESIGN

The leadless sensor capsule is comprised of two main components, the sensor chip and the cover wafer which are eventually assembled to form the pressure capsule.
The sensor chip is manufactured from two separate wafers. First a carrier wafer is fabricated which forms the mechanical structure, the diaphragm. The second wafer is referred to as the sacrificial wafer on which is defined the areas which the high conductivity P^+ piezoresistive strain gauges occupy. After oxidising the carrier wafer to form an electrically insulating layer over its surface, the two wafers are bonded together using a Diffusion Enhanced Fusion bonding (DEF) process [8], [9]. The bond is a direct chemical molecular bond between the P^+ regions and the silicon oxide and uses no adhesive or additional components. Once the bond is formed, the non-doped areas of the carrier wafer are selectively removed chemically. The piezoresistive P^+ are now permanently bonded to the dielectrically isolated carrier wafer in which the diaphragm is now micromachined. In order to optimise the mechanical performance of the force collector, the diaphragm is formed in the shape of a picture frame [10].
Figure 5 shows a view of the sensor chip with the four piezoresistive gauges strategically positioned inside the "picture frame" and connected in a Wheatstone bridge. The entire sensing network is P^+ and there are separations between the contact regions of the bridge, Metal is deposited to form ohmic contacts to the P^+ regions located inside the large contact regions. There is also a rim of P^+ material around the periphery of the sensor chip. When the cover wafer is assembled to the sensor chip, an hermetic seal is formed between the cover and this area of P^+ material thus protecting the stress sensing network and all the electrical interconnections from the harsh environmental conditions.

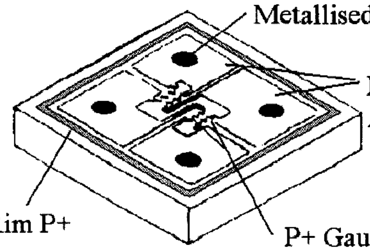

Figure 5.

The cover wafer is manufactured from either silicon or a Pyrex glass to the same dimensions as the silicon wafer. Four holes are drilled in the cover, one in each corner, which align with the metallised contact pad areas. A recess is also created in the centre of the cover wafer to allow the diaphragm to deflect freely when assembled.
The sensor chip and the cover wafer are then assembled using an electrostatic bond. Figure 6 shows a top isometric view of the components just prior to sealing. Once the two wafers have been bonded, only the metallised leadout pads are exposed whilst all the gauges and electrical interconnections on the sensing side of the silicon chip are sealed by the cover. Thus the active portion of the pressure sensor is hermetically isolated.

8. THE LEADLESS CONNECTION

To avoid the use of gold ball bonds and fine gold wires, a high temperature metal frit is used to provide the electrical connection between the sensing chip and a specially designed header. The frit is a mixture of high conductivity metal powders in appropriate physical form and glass and is used to fill the holes in the cover wafer after it is bonded to the sensor chip.
The specially designed header contains a group of four hermetically sealed pins protruding from its surface which are spaced so as to fit the holes drilled in the cover wafer. Figure 7 shows a section of the assembled pressure capsule and also a section of the pressure capsule mounted in the header. The pressure capsule is bonded to the header at a high temperature using a non conductive glass frit, during which process the metal frit in the cover wafer holes melts and creates low resistance electrical connections between the header pins and the metal contact pads on the sensor chip.

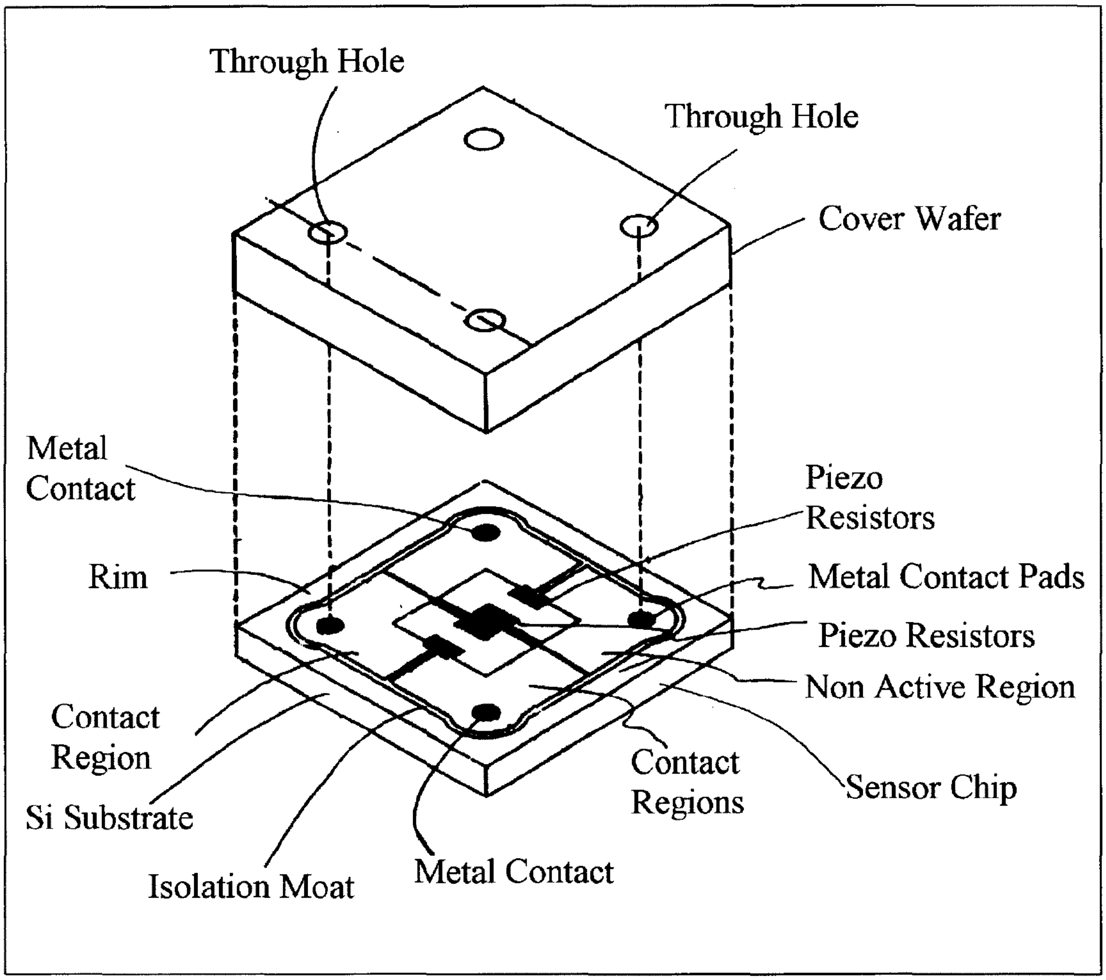

Figure 6

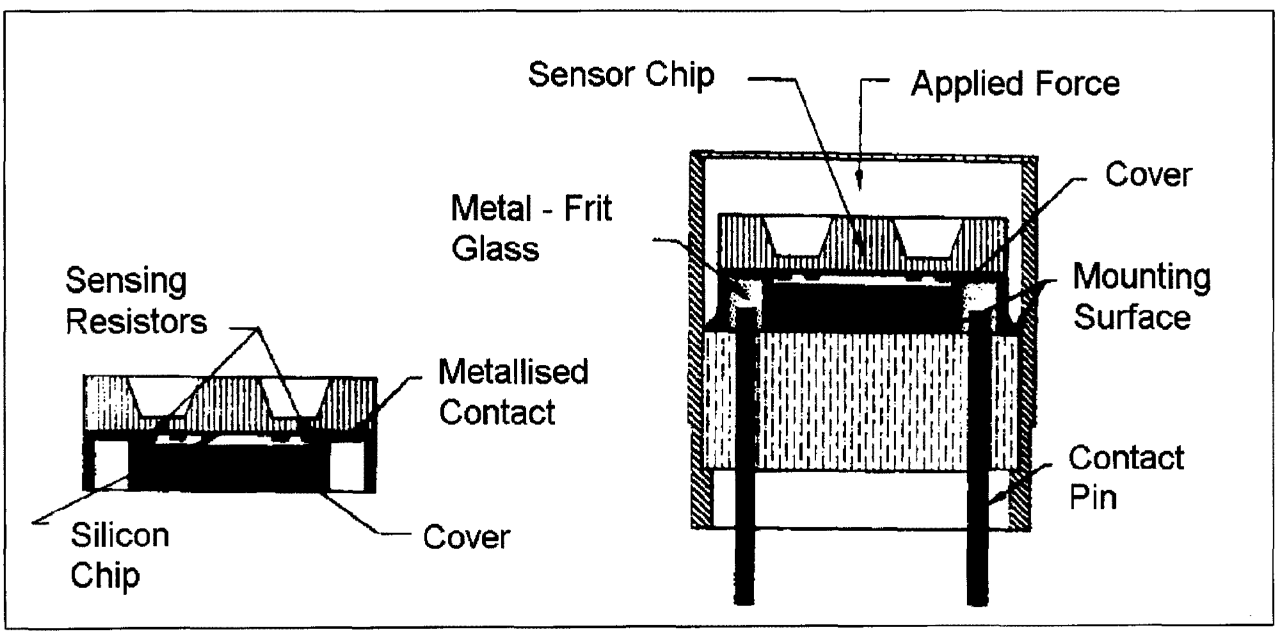

Figure 7

After this firing process, only the non-active side of the diaphragm is exposed to the pressure medium. The small ball bonded gold leads have been eliminated and the entire sensor network and contact areas are hermetically sealed from the environment and the pressure media.

9. TRANSDUCER ASSEMBLY

The hermetically sealed pressure sensing capsule bonded to the header is the starting point for the assembly into a pressure transducer. Typically most transducers must be attached to a mounting surface which is exposed to the pressure media, frequently by means of a threaded port. In addition, the header pins must be electrically connected to a high temperature cable assembly without the use of solder joints which may fail at high temperatures. The high temperature cable assembly must also contain material which will provide electrical insulation between individual leads, whilst the interconnects between the header and the cable as well as the cable itself must be strong enough to withstand the mechanical stresses of handling. The package is completed using a building block approach and Figure 8 shows the assembly of a typical ultra high temperature leadless pressure transducer.

A sleeve (1) is welded between the first header and a second header. A minerally insulated (MI) cable containing nickel wires is used to interconnect to the pins from the first header and the exposed leads from the first header are welded to the second header to ensure low resistance electrical connections between the leads of the MI cable and the header leads.

The header/ MI cable assembly is then inserted into a port (2) and welded to the port. At the end of the port is a tubulation (4) which is crimped to retain the MI cable.

A cover sleeve is then assembled over the MI cable to give additional support and is welded to the rear of the cover (5) which in turn is welded to the port (2).

This design of assembly results in the transducer being totally hermetically sealed from any atmospheric contamination or oxidation. Every single internal metallised surface such as metal to silicon and metal to glass frit, header pins to header tubes, header pins to MI cable wires and even the mineral insulation itself is hermetically sealed from the atmosphere. In addition the welding of the sleeve to the port together with the addition of the third header greatly increases the structural integrity of the entire electrical interconnect system and reduces the chances of any damage in severe environments.

10. STATIC PERFORMANCE

The first generation of leadless transducers (five units) have been tested in the laboratory with the following results. Figure 9 shows the change in zero output during repeated temperature cycling between room temperature and 455°C (850°F). This demonstrates that exposure to high temperatures has negligible effect on the internal electrical connections and contacts. A few ohms change in a contact resistance would result in changes in the output of many millivolts. All observed changes in output were less than 2 mV. Figure 10 plots the full scale output at 455°C (850°F) for two sensors over repeated cycles. Stable and repeatable outputs were observed throughout this study.

Figure 11 shows the pressure v output voltage performance measured at room temperature, 177°C (350°F), 343°C (650°F) and 455°C (850°F) for one of the sensors. There is a small element of zero shift but the unit is very linear and exhibits a repeatable span shift of approximately 2-3%/100°C (1-2%/100°F). Figure 12 shows sensor performance up

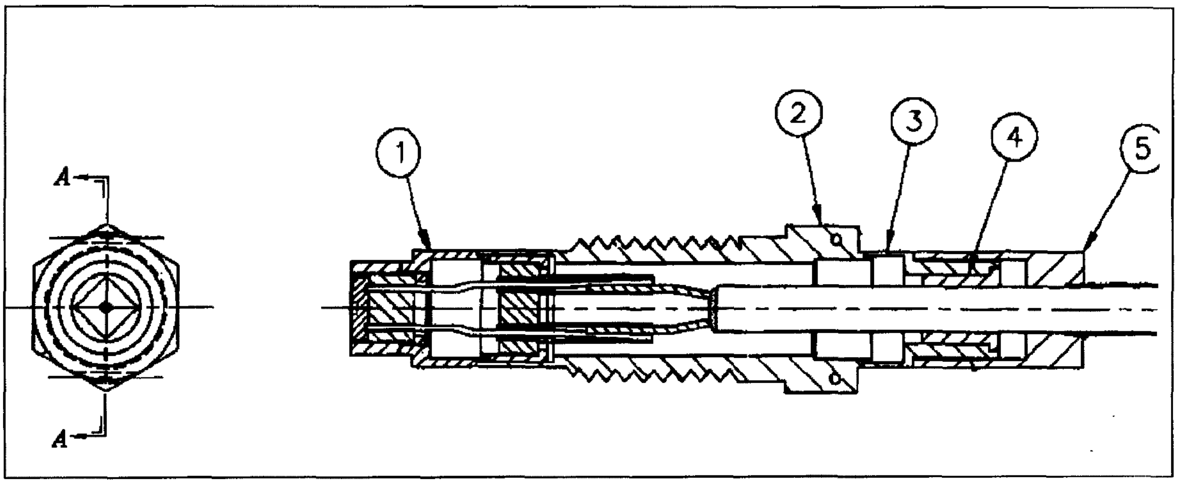

Figure 8

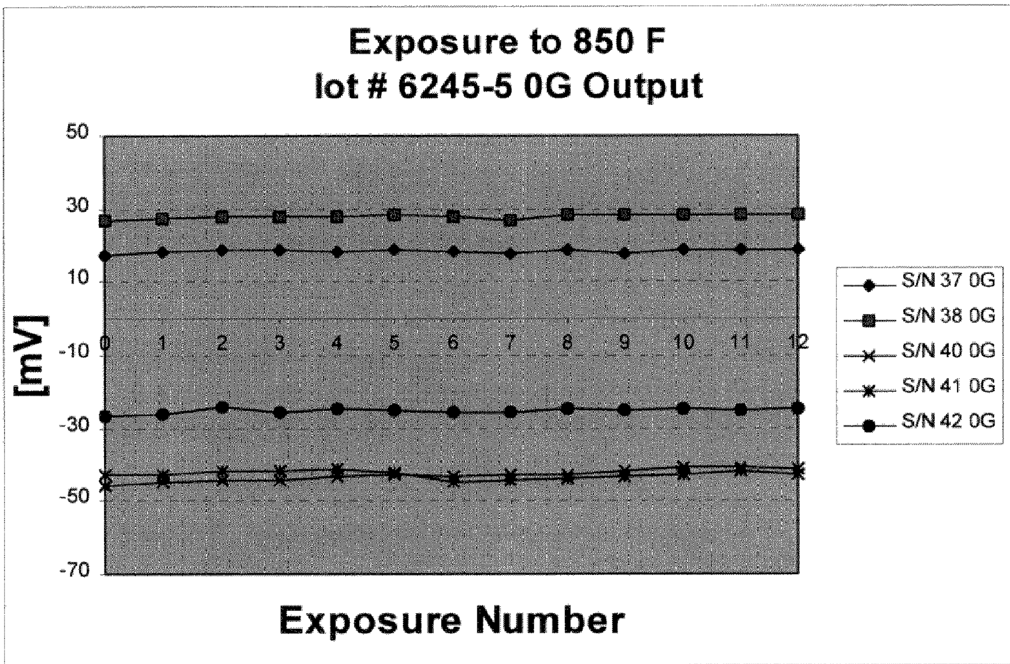

Figure 9

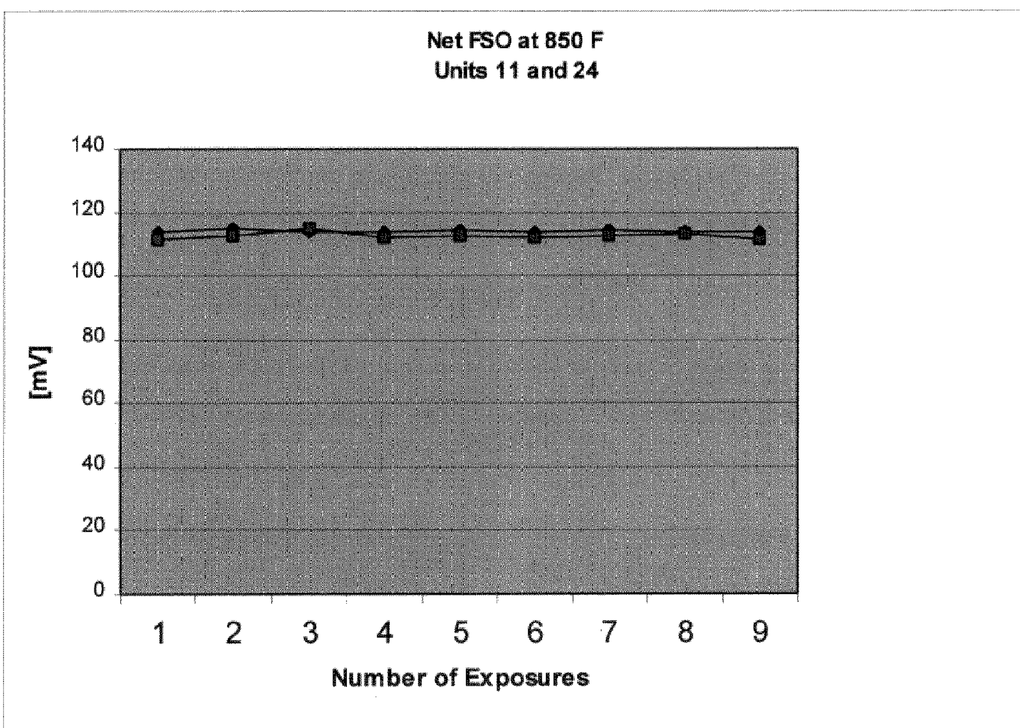

Figure 10

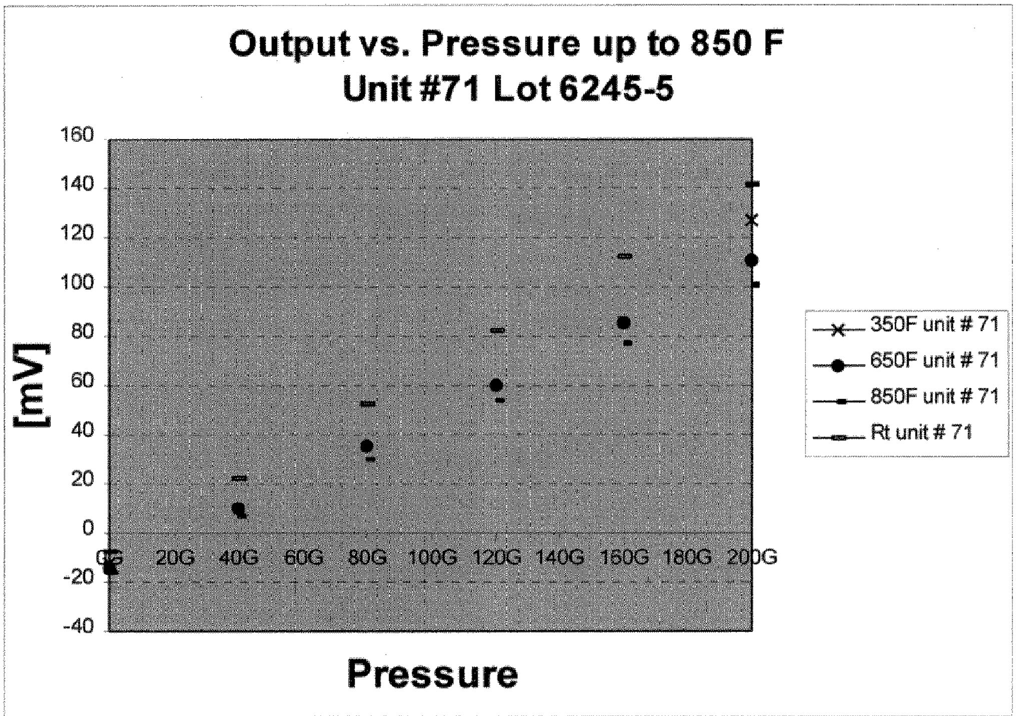

Figure 11

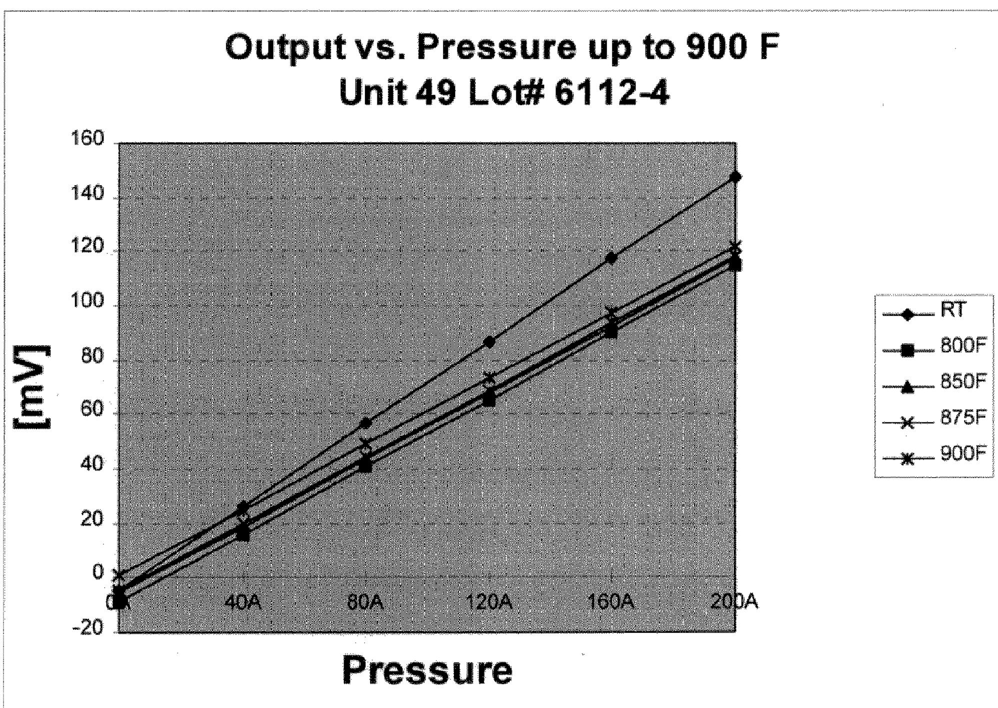

Figure 12

to 482°C (900°F) for another one of the tested sensors. Linearity and span shift remain virtually identical.
Test data from the latest generation of leadless transducers manufactured have confirmed the original results.
To summarise the test results, the devices appear to have less than 0.02%F.S. non-linearity and no measurable hysteresis up to temperatures of 482°C (900°F). At temperatures of 454°C (850°F) the non-linearity increases to around 0.1%F.S. but a static error band of better than 0.15%F.S. can be expected. All units tested exhibited only minor changes in performance characteristics after repeated exposure to high temperatures. When the latest units were compensated, span and zero shifts of less than 1%F.S. over the temperature range from room temperature to 480°C (900°F) were achieved.

11. DYNAMIC PERFORMANCE

The design of the high temperature sensor is such that it should have high frequency response characteristics similar to those of more familiar, low temperature capability Kulite sensors. To verify this experimentally, a pulsed air apparatus was set up in an oven. The frequency response test configuration is shown in Figure 13.

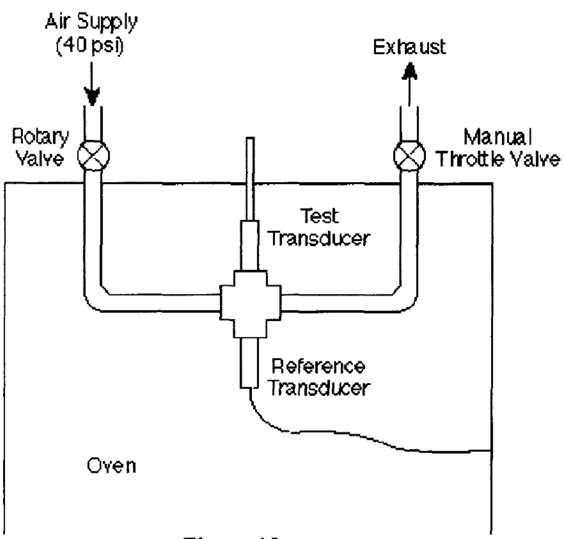

Figure 13

Large scale pressure primary pulsations at frequencies up to 400-500Hz were generated by a water cooled, motor driven rotary valve with an 1/4" port. The valve was close mounted externally to an oven containing the test transducer. About 15 cm of 1/4" stainless steel line connected the valve to the transducer, which was mounted on one leg of a T-piece inserted in the line. A second, standard, lower temperature capability transducer (model XTC-190) was mounted in the opposite leg of the T. The air flow, after passing by the transducers, exited the oven through 15 cm of line to a manual throttle valve.
The response of both transducers was first established at room temperature. The high temperature unit and low temperature reference unit had essentially identical waveform shapes and frequency responses. This verified that the transducers and test arrangement were responding as expected. The reference unit was then removed and the test repeated at elevated temperatures, after an appropriate soak time.
An example of the transducer response at 650 F when subjected to a nominally 250 Hz sinewave excitation is shown in Figures 14 and 15.

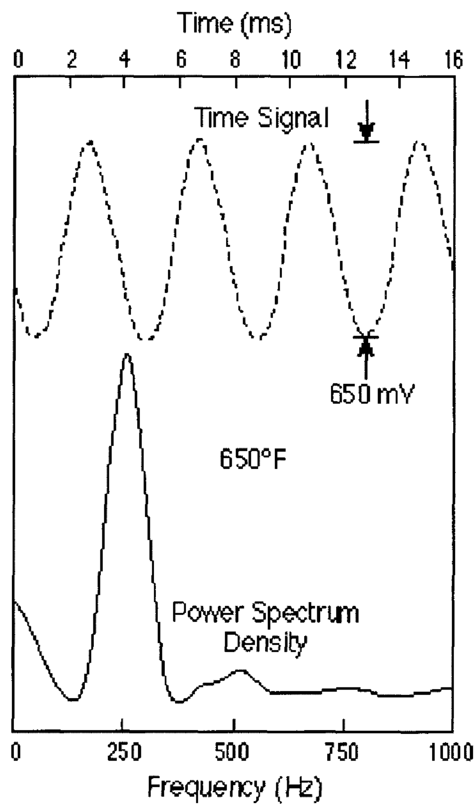

Figure 14

The amplifier gain used was 200. At the higher frequency of 400Hz, the wave form is less sinusoidal due to resonance in the flow system. The second harmonic response is clearly visible at 800Hz. These tests are greatly constrained by the limitations of the excitation mechanism and so do not fairly illustrate the frequency response capabilities of the sensor, which is in excess of many tens of kilohertz. The data do however, demonstrate nearly ideal ac response through the range of interest for many gas turbine active control applications.

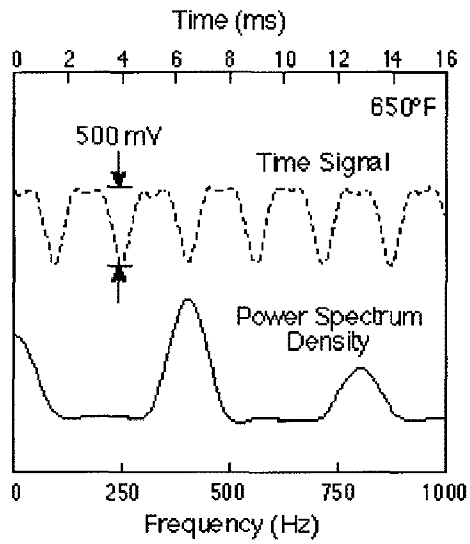

Figure 15

11. CONCLUSIONS

The latest generation of leadless sensors have been designed, fabricated and evaluated within Kulite with very encouraging results. The key features of the leadless design, which are protected by U.S. Patent Number 5,955,771, are the elimination of the gold ball bonding and gold lead wires and the hermetic sealing of the pressure capsule and the transducer assembly which will enable these transducers to operate reliably in the most hostile environments.

Currently these second generation leadless dynamic pressure transducers are being evaluated both in laboratories and on gas turbines by the majority of the US and European aero engine manufacturers and many aerospace industry test organisations. The results of these test program will be the subject of further technical papers.

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Rolls-Royce, Derby, UK
Scientific Systems Co. Inc., Woburn, MA
SNECMA, Paris
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PAPER -12, J. W. H. Chivers

Question (W. Riess, Germany)
What is the price level of the sensor?

Reply
After commercial introduction, a price range similar to that charged for other aerospace pressure transducers used for the measurement of oil, fuel, hydraulic oil, etc is possible. I.e., US$ 1000-1200 per unit in quantity.

Question (S. Candel, France)
Are these sensors sensitive to acceleration and were you able to test them in high amplitude vibrational environments?

Reply
The leadless sensor has an acceleration sensitivity, but it is extremely small. It is similar to the sensitivity of other miniature Kulite pressure transducers, i.e., 0.00005% full scale output per g.

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